Jet Propulsion Laboratory
California Institute of Technology

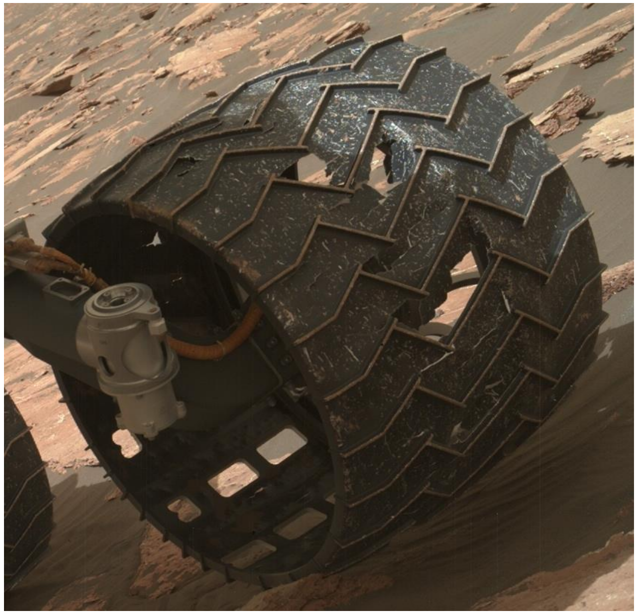
Traction Control Design and Integration Onboard the Mars Science Laboratory Curiosity Rover

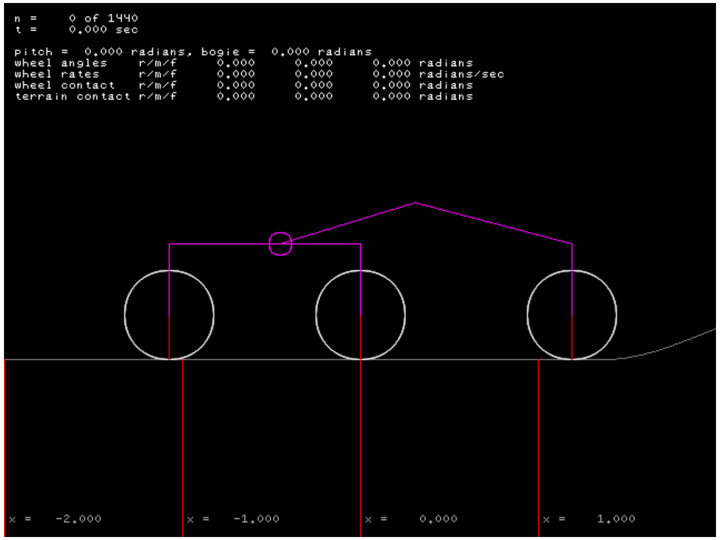
IEEE Aerospace Conference
Big Sky, MT
March 9, 2018

Olivier Toupet, J. Biesiadecki, A. Rankin, A. Steffy,
G. Meirion-Griffith, D. Levine, M. Schadegg, M. Maimone
Research Technologists, JPL

Motivation

- **State-of-practice**: control wheels assuming flat terrain
- **Goal**: control wheels to account for undulated & rocky terrain
- **Why?** To reduce slip in order to:
  - Minimize wheel wear
  - Reduce sinkage in sand
  - Reduce energy consumption
  - Minimize rover deviation from its planned path

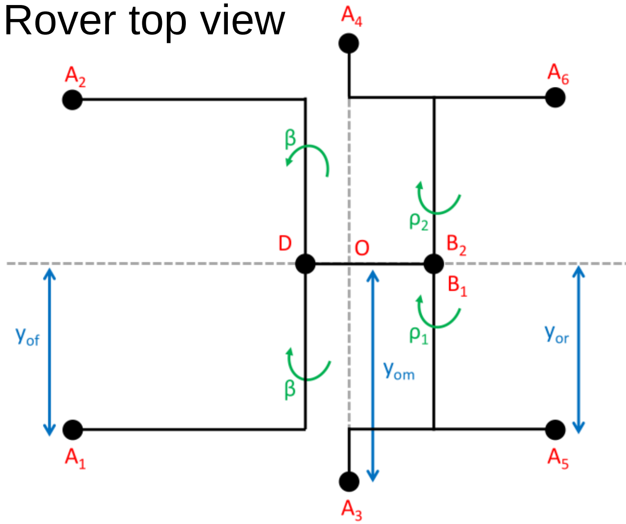


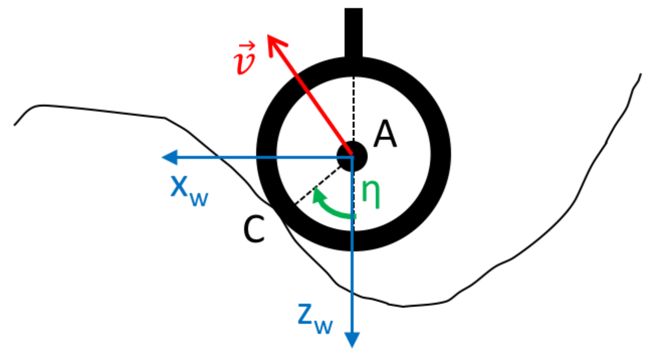


- Rover modelled as an articulated system of rigid bodies

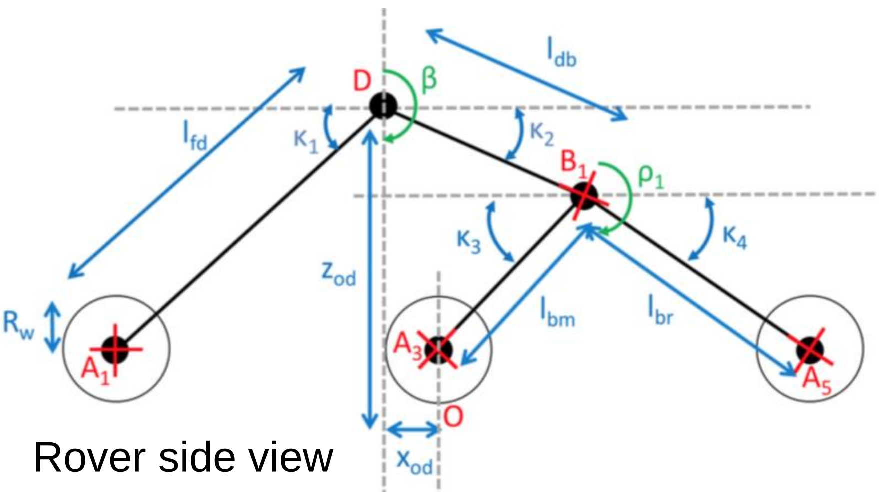
Legend:
$rk_{1/2}$: left / right rocker
$Bg_{1/2}$: left / right bogie
bd: rover body frame
O: rover origin
D: differential joint
$B_{1,2}$: left/right bogie joint
A_i: center of wheel i
v: velocity
ω: angular rate

Rover top view





Wheel-ground contact modelled as a **single point** without loss of generality



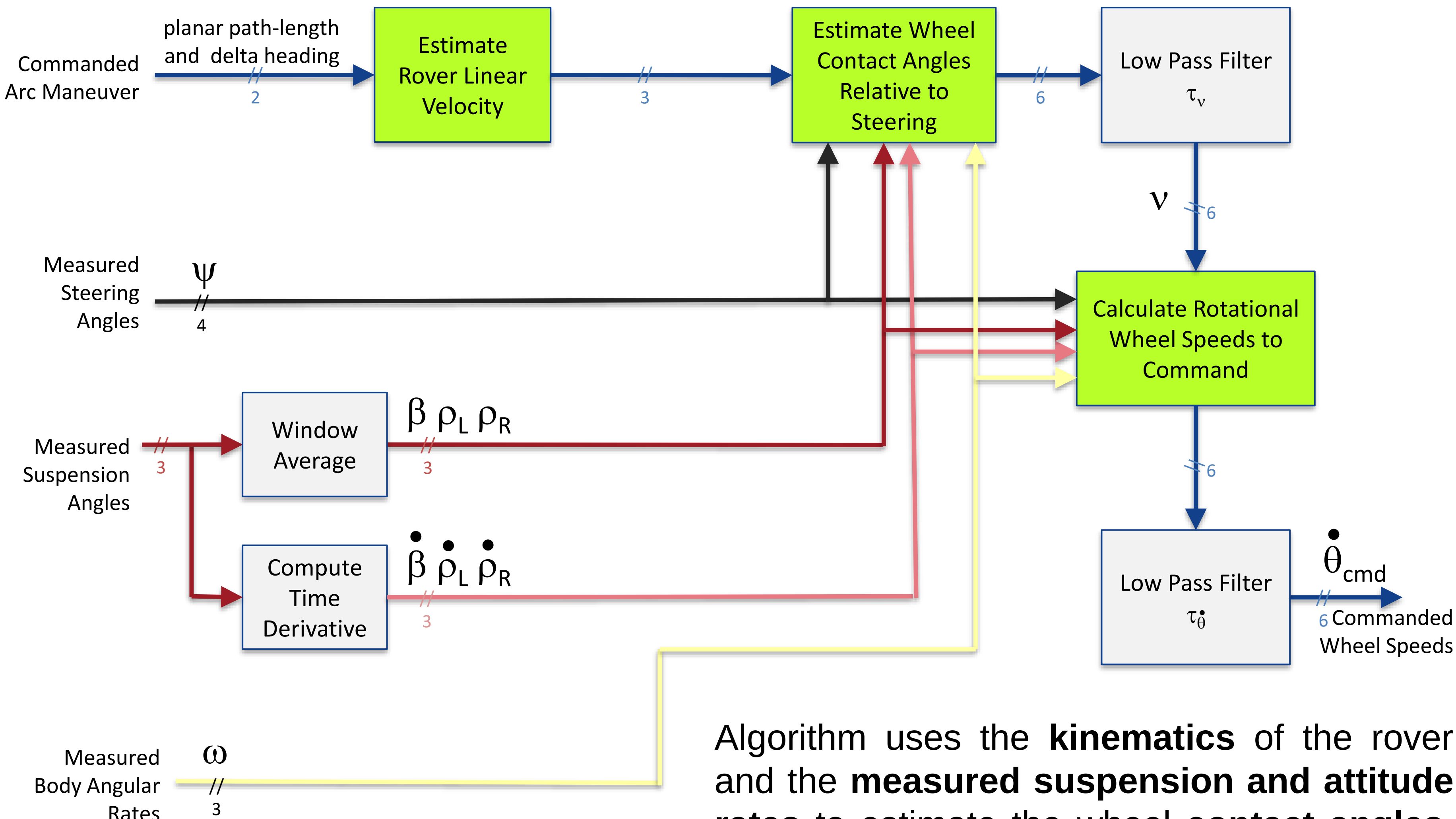
Rover side view

Key kinematic relationship:

$$ {}^{\mathcal{F}}\vec{v}_A = {}^{\mathcal{F}}\vec{v}_B + {}^{\mathcal{F}}\vec{\omega} \times {}^{\mathcal{F}}\vec{BA} $$

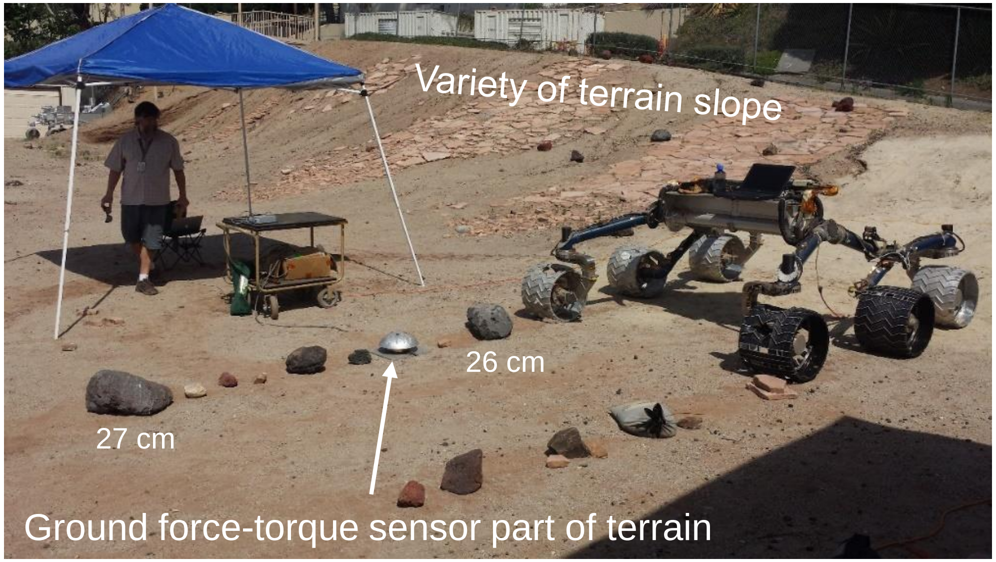
Used to **relate the wheels linear velocities** to the **rover origin's linear velocity**, the **attitude and suspension rates**, and the **rover geometry**

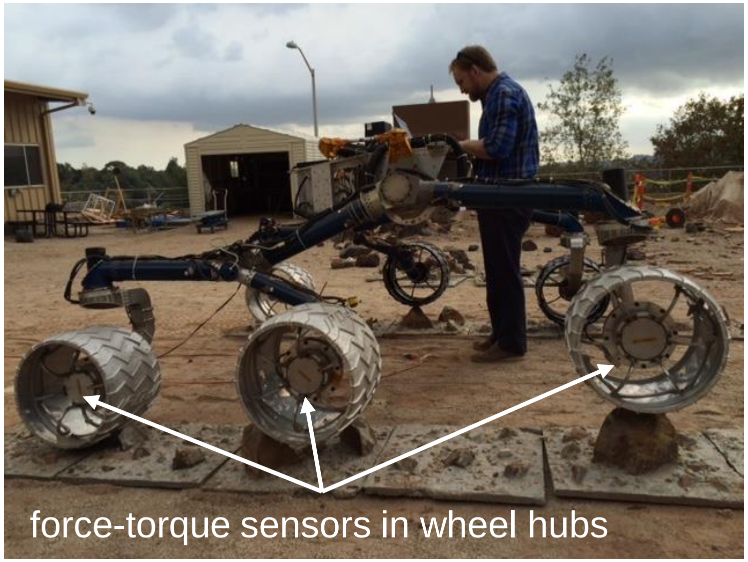
Technical Approach: Functional Block Diagram

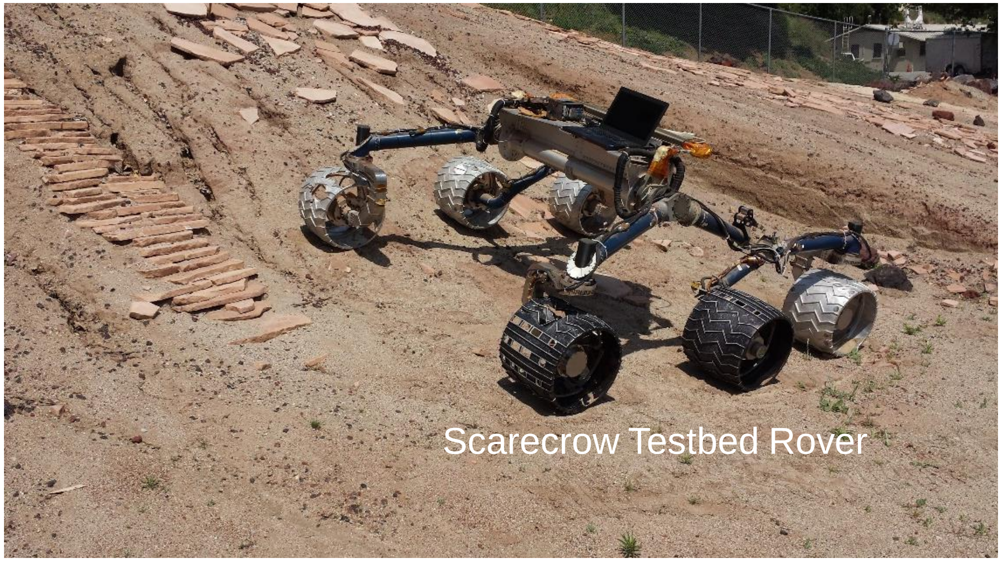


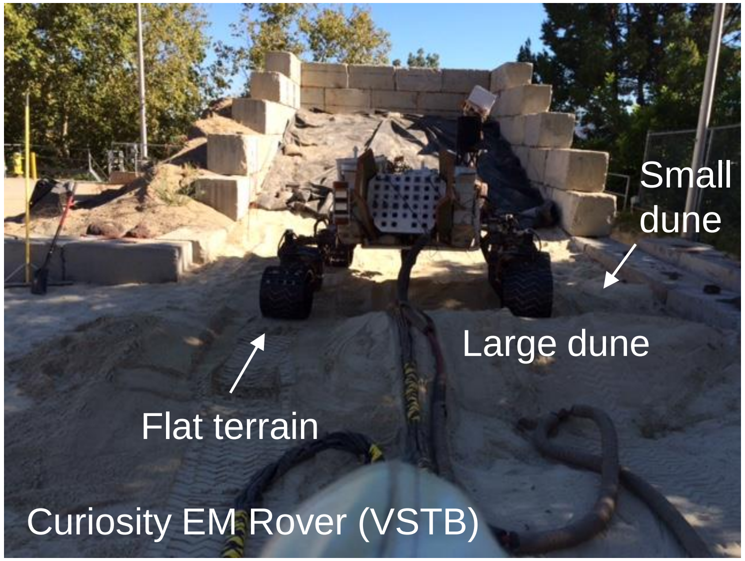
Algorithm uses the **kinematics** of the rover and the **measured suspension and attitude rates** to estimate the wheel **contact angles**, and then compute the **no-slip wheel rates**

Performance in Test: JPL Mars Yard









Performance in Test: Illustration of Slip Reduction

TRCTL disabled

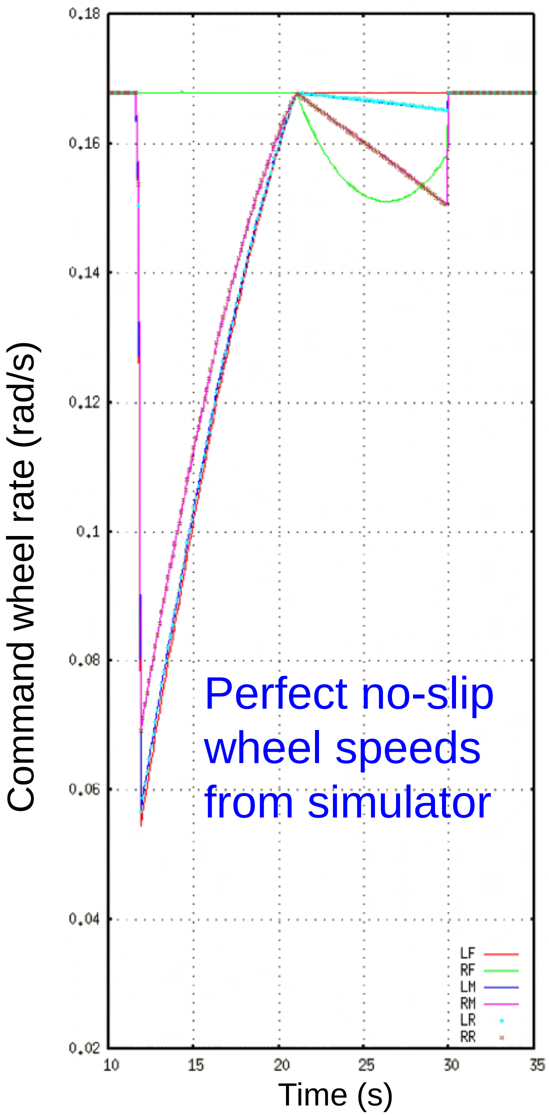
- All wheels commanded the same angular rate
- Note LF wheel slip
- Loading on LM wheel increased by LF wheel pulling it into the rock and LR pushing it into the rock

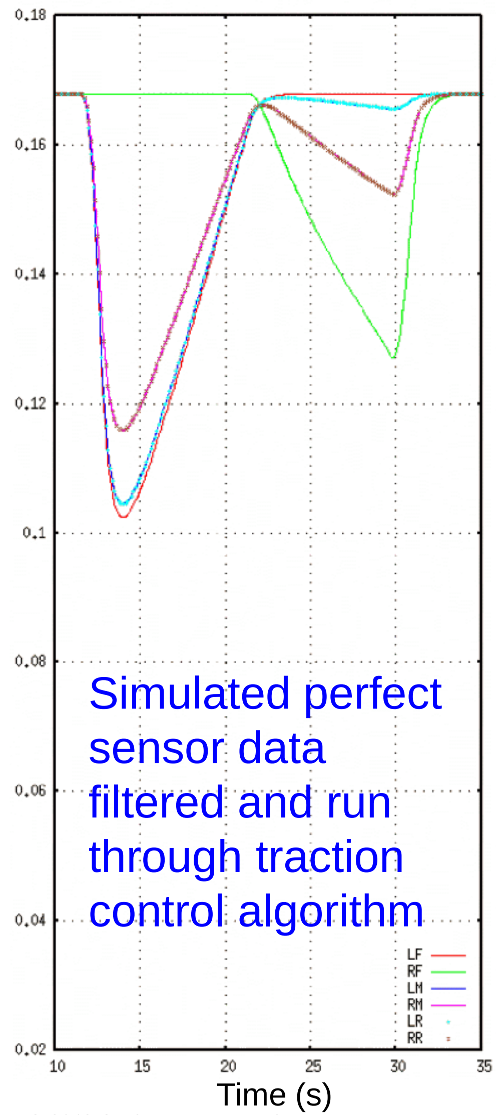
TRCTL enabled

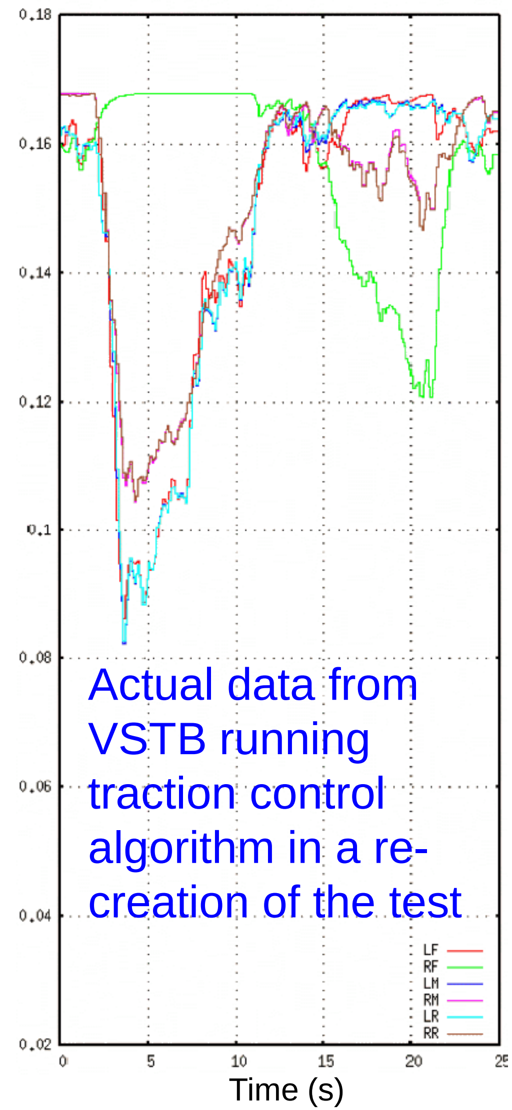
- LM is commanded the max angular rate; other wheels are slowed down
- Reduces LF and LR slip and loading on the LM

Performance in Test: Wheel Rate Commands

Forward straight arc with RF wheel over dome

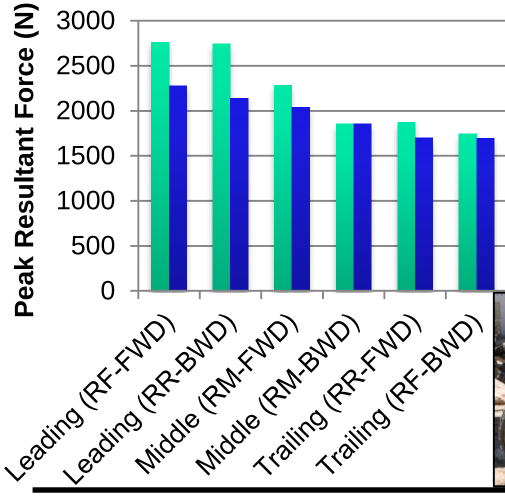






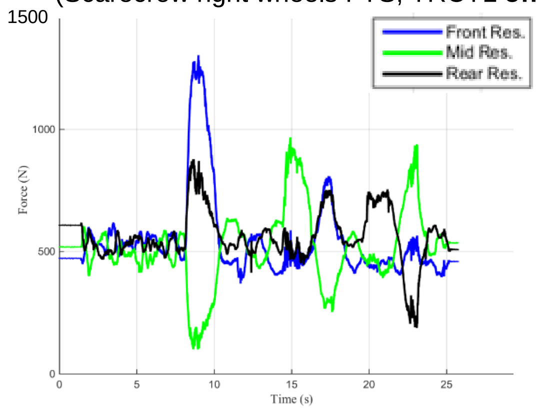
Performance in Test: Representative Results

VSTB fwd and bwd over the dome

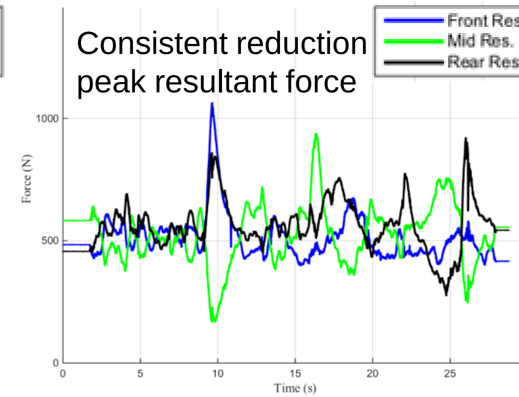


Scarecrow over the dome

Resultant force magnitude
(Scarecrow right wheels FTS, TRCTL **off**)

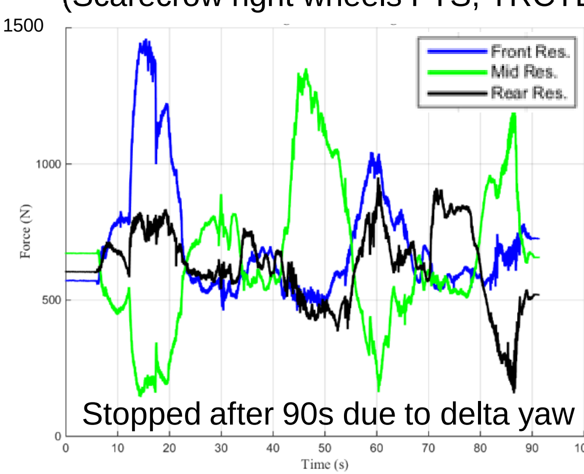


Resultant force magnitude
(Scarecrow right wheels FTS, TRCTL **on**)

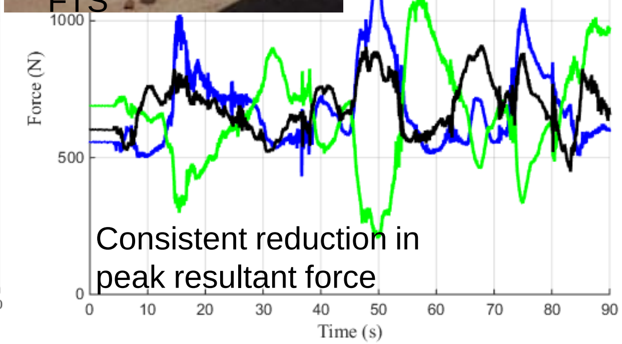


Scarecrow over complex terrain

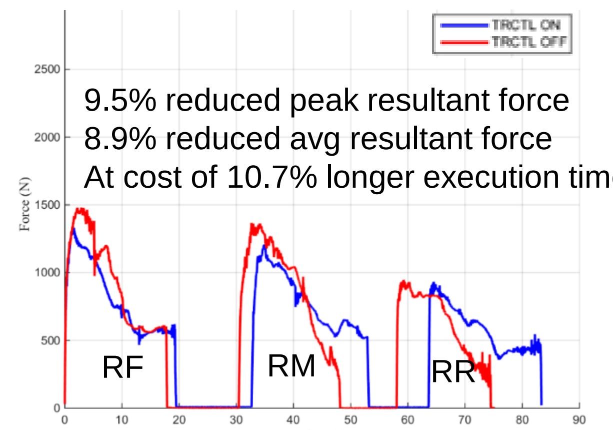
Resultant force magnitude
(Scarecrow right wheels FTS, TRCTL **off**)



Resultant force magnitude
(Scarecrow right wheels FTS, TRCTL **on**)

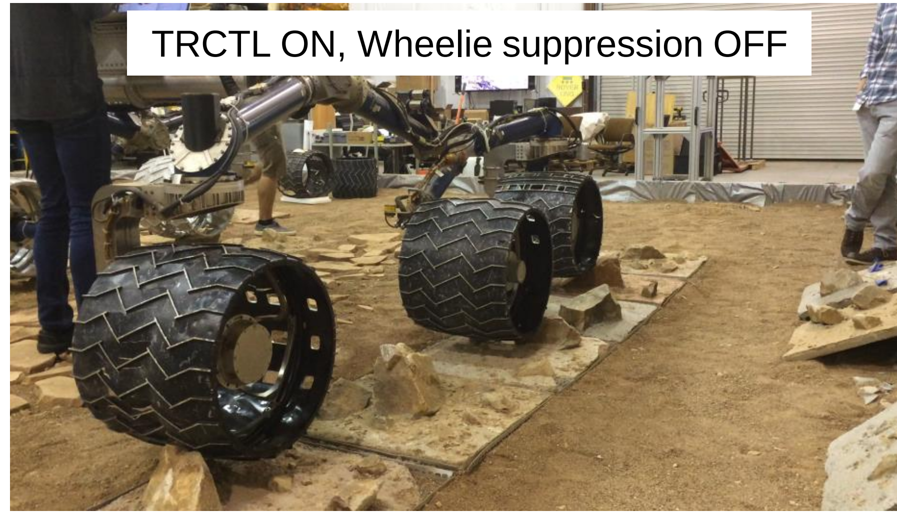


Resultant force magnitude
Scarecrow right wheels over ground FTS)



Performance in Test: Illustration of Wheelie Suppression

- Repeatable mid-wheel “wheelie” was observed on dense, embedded-rock terrain when TRCTL was enabled
  - Mid wheel crests a rock
  - Rear wheel on flat terrain
  - Descending front wheel pushes against an embedded rock
  - Mid wheel continues to climb
- Mid and rear wheel “wheelie” detection/suppression code was implemented
  - Threshold wheel current, bogie angle, and bogie angle rate
  - If mid wheel “wheelie” is detected, slow down rear wheel
  - If rear wheel “wheelie” is detected, slow down mid wheel



Symmetric track constructed with cement tiles containing ≤ 20cm tall embedded rocks

Integration into Mission Operations

Date	Milestone
Oct 2013	MAHLI images revealed unexpected high wheel damage rate. Wheel wear tiger team was assembled.
Jan 2015	A full flight software update (release R12) was deployed on Curiosity. It included software hooks to simplify later integration of TRCTL (command to enable/disable, parameter fields, telemetry fields, function pointer to evaluate drive rates at 8Hz)
Spring 2014 - Aug 2016	Algorithm development testing TRCTL software was compiled as a single object file
Sep 2016	Validation and Verification testing in JPL Mars Yard on the VSTB
Mar 2017	Software Review Certification Record (SRCR) Review
Mar 2017 - Apr 2017	Three checkout tests were performed on Mars (Sol 1644: Upload TRCTL hot patch and save parameters to NVM, Sol 1646: 5m drive with TRCTL enabled, Sol 1662: 20m drive with TRCTL enabled)
Apr 2017	Checkout Test Review. TRCTL was approved for nominal use on Mars starting Sol 1678

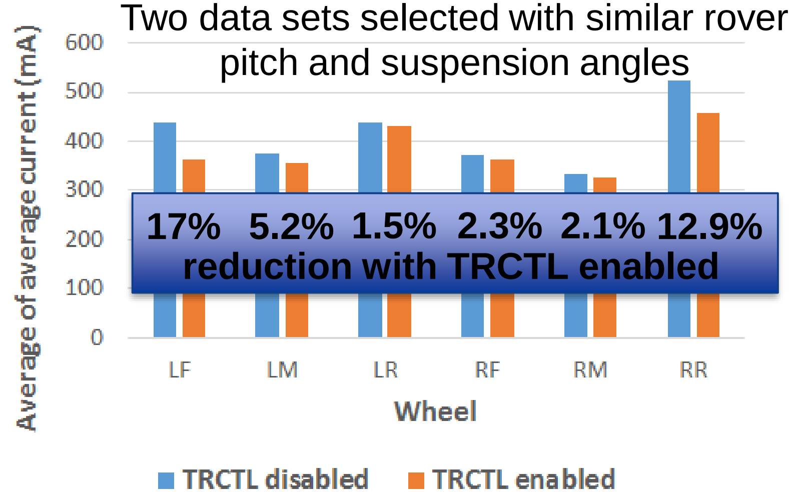
Performance in Flight

Number of sols TRCTL has been used (as of 12/04/2017)	80*
Total TRCTL odometry	1,693.0 m
Non-TRCTL odometry since TRCTL was approved	17.5 m**
Number of drives that stopped early due to TRCTL timeout	1
Avg compressed Mob data product size w/ TRCTL enabled	1.98x (1.90x modeled)
Avg traverse rate reduction	13.8% (15% modeled)

	1km before Sol 1678 (42.61m elev increase)^	1km after Sol 1678 (69.49m elev increase)^^
Mean of max current for each drive step	368mA	345mA (6.3%)
Mean of mean current for each drive step	350mA	321mA (8.3%)

^Excluded currents during TRCTL checkout (25m)
^^1.7x higher average terrain upslope

Two data sets selected with similar rover pitch and suspension angles



(Sols 1664-1677) (Sols 1678-1707)

****Includes two checkout tests (Sols 1646 and 1662)***
*****Four FMWI (5m), 1st 2.5m recovering from Sol 1787 fault, 10m leg on Sol 1800, 7cm step on Sol 1846***

Conclusion

- Lessons learned during development
  - Performance is degraded by noisy measurements, backlash in suspension joints, etc
  - Testing on rough, high-friction terrain motivated an algorithm extension to detect and correct bogie wheelies
  - Compromised performance for robustness
- Flight Performance
  - Average reduction of mean wheel current per drive of 8.3%*
  - Average reduction of max wheel current per drive of 6.3%*
  - In a comparison of two drive data sets on similar terrain:
    - average reduction in wheel currents of 10% for the front wheels and 7% for the rear wheels
    - Average reduction of maximum rover slip per drive of 2.1%
  - Benefits of reduced forces on the wheels outweigh the costs (11.2% longer traverse time and 1.91x larger motion history recorded data)

*Comparing 1km before and after nominal use of TRCTL for all 6 wheels

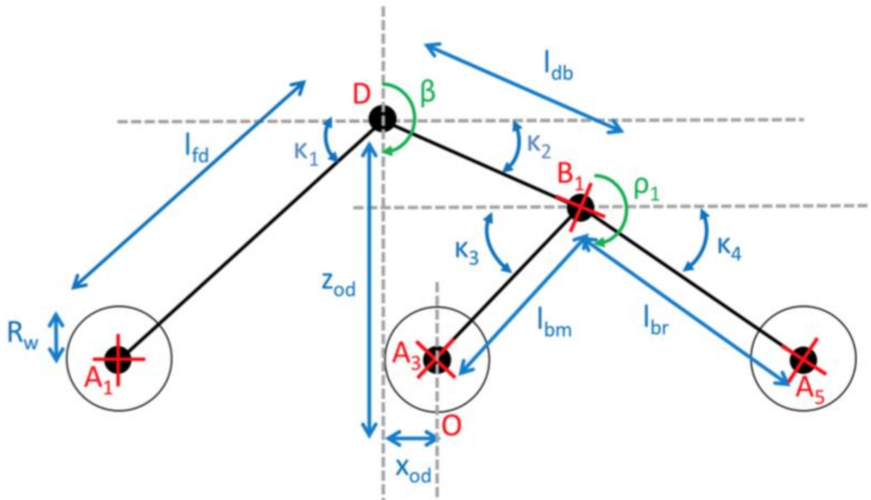
Future Work

- Possible use of camera under rover's belly to better estimate rover body velocity
- Incorporate torque feedback into wheel speed commanding to better achieve desired torque at each wheel as a function of contact angle
- Future rover missions are considering TRCTL use to benefit from the reduced yaw error and slip

Backup

Technical Approach (1/4)

- For two points A & B on the same rigid body:
  - ${}^{F}v_{A} = {}^{F}v_{B} + {}^{F}\omega_{bd} \times {}^{F}BA$ **(1)**
  - Where ω_{bd} is the angular velocity vector of the rigid body relative to the inertial frame, and F is any Cartesian frame



rk_1: left rocker, rk_2: right rocker
bg_1: left bogie, bg_2: right bogie
bd: rover body frame
O: rover origin (RNAV)
D: differential joint
$B_{1,2}$: left/right bogie joint
A_i: center of wheel i

- By applying this equation to each linkage: $O \rightarrow D \rightarrow B_{1,2} \rightarrow A_{3,4,5,6}$; $D \rightarrow A_{1,2}$
  - ${}^{bd}v_{O} = [x_{dot}\ y_{dot}\ z_{dot}]$
  - ${}^{bd}v_{D} = {}^{bd}v_{O} + {}^{bd}\omega_{bd} \times {}^{bd}OD$
  - ${}^{bd}v_{A_{1,2}} = {}^{bd}v_{D} + {}^{bd}\omega_{rk_{1,2}} \times {}^{bd}DA_{1,2}$ **(2)**
  - ${}^{bd}v_{B_{1,2}} = {}^{bd}v_{D} + {}^{bd}\omega_{rk_{1,2}} \times {}^{bd}DB_{1,2}$
  - ${}^{bd}v_{A_{3,4,5,6}} = {}^{bd}v_{B_{1,2}} + {}^{bd}\omega_{bg_{1,2}} \times {}^{bd}B_{1,2}A_{3,4,5,6}$

We can relate the wheels linear velocities to the rover origin's linear velocity, the attitude and suspension rates, and the rover geometry

Technical Approach (2/4)

- To compute the wheels' angular rates, we need to compute the wheels' linear velocities in the contact angle frame:
  - ${}^{bd}v_O = [x_{dot}\ 0\ z_{dot}]$
  - ${}^{bd}v_D = {}^{bd}v_O + {}^{bd}\omega_{bd} \times {}^{bd}OD$
  - ${}^{\eta 1}v_{A_1} = {}^{\eta 1}R_{bd} \times ({}^{bd}v_D + {}^{bd}\omega_{rk_1} \times {}^{bd}DA_1) = [R_w\theta_{dot\_1}\ ?\ 0]$
  - ${}^{\eta 2}v_{A_2} = {}^{\eta 2}R_{bd} \times ({}^{bd}v_D + {}^{bd}\omega_{rk_2} \times {}^{bd}DA_2) = [R_w\theta_{dot\_2}\ ?\ 0]$
  - ${}^{bd}v_{B_1} = {}^{bd}v_D + {}^{bd}\omega_{rk_1} \times {}^{bd}DB_1$
  - ${}^{bd}v_{B_2} = {}^{bd}v_D + {}^{bd}\omega_{rk_2} \times {}^{bd}DB_2$
  - ${}^{\eta 3}v_{A_3} = {}^{\eta 3}R_{bd} \times ({}^{bd}v_{B_1} + {}^{bd}\omega_{bg1} \times {}^{bd}B_1A_3) = = [R_w\theta_{dot\_3}\ ?\ 0]$
  - ${}^{\eta 4}v_{A_4} = {}^{\eta 4}R_{bd} \times ({}^{bd}v_{B_2} + {}^{bd}\omega_{bg2} \times {}^{bd}B_2A_4) = [R_w\theta_{dot\_4}\ ?\ 0]$
  - ${}^{\eta 5}v_{A_5} = {}^{\eta 5}R_{bd} \times ({}^{bd}v_{B_1} + {}^{bd}\omega_{bg1} \times {}^{bd}B_1A_5) = = [R_w\theta_{dot\_5}\ ?\ 0]$
  - ${}^{\eta 6}v_{A_6} = {}^{\eta 6}R_{bd} \times ({}^{bd}v_{B_2} + {}^{bd}\omega_{bg2} \times {}^{bd}B_2A_6) = [R_w\theta_{dot\_6}\ ?\ 0]$

Wheels can slip laterally some unknown amount due to imperfect steering when turning on non-flat terrain

- This gives us 2 equations per wheel:
  - the x component gives us the wheel rate:

$$\theta_{dot\_i} = f(x_{dot}, z_{dot}, \omega_x, \omega_y, \omega_z, \beta, \beta_{dot}, \rho_j, \rho_{dot\_j}, \eta_i) \qquad \textbf{(3)}$$

attitude rates rocker angle bogie angle contact angle

  - the z component gives us an extra relationship:

$$g(x_{dot}, z_{dot}, \omega_x, \omega_y, \omega_z, \beta, \beta_{dot}, \rho_j, \rho_{dot\_j}, \eta_i) = 0 \qquad \textbf{(4)}$$

Technical Approach (3/4)

- What are the unknowns?
  - x_{dot}, z_{dot}: linear velocity of rover origin ($y_{dot}=0$: no lateral move on purpose)
  - η_i: the contact angle of each wheel

- The contact angles can be estimated separately
  - Option 1: use the kinematic equation (1) for chosen pairs of wheels to extract the contact angles based on the measured wheel rates*
    - More accurate estimates but makes input dependent on output
    - Not robust to measurement errors (e.g. wheel slip)
  - Option 2: compute the CAEs based on the planar rover linear velocity:

    $\eta_i = \mathrm{atan}(-{}^{w_i}v_{A_i}^{\,z} \,/\, {}^{w_i}v_{A_i}^{\,x})$ **(5)**

    with ${}^{w_i}v_{A_i} = {}^{w_i}R_{bd}\,{}^{bd}v_{A_i}$ the wheel velocity in the wheel frame, and ${}^{bd}v_{A_i}$ computed from (2) using the planar rover linear velocity

- Now we can compute the ideal wheel rates θ_{dot_i} to achieve a desired x_{dot}:
  a) Use equation (5) to substitute η_i in equations (3) and (4)
  b) Use equation (4) to get $z_{dot} = h(x_{dot}, \omega_x, \omega_y, \omega_z, \beta, \beta_{dot}, \rho_j, \rho_{dot\_j})$ **(6)**
  c) Use (6) to substitute z_{dot} in equation (3) and get:

     $\theta_{dot\_i} = f(x_{dot}, \omega_x, \omega_y, \omega_z, \beta, \beta_{dot}, \rho_j, \rho_{dot\_j})$ **(7)**

     all known

* K. Iagnemma, S. Dubowsky "Vehicle Wheel-Ground Contact Angle Estimation: With Application To Mobile Robot Traction Control", *Proceedings Int'l. Symposium Advances in Robot Kinematics*, 2000.

Technical Approach (4/4)

- In reality we don't command the rover by specifying a desired x_{dot} but by turning the wheels as fast as possible, up to their limit θ_{dot_max}

- To achieve this we proceed as follows:
  a) Compute x_{dot} for each wheel using equation (7) with $\theta_{dot} = \theta_{dot\_max}$
  b) Find the wheel that achieves the min x_{dot}: this is the limiting wheel
  c) Set x_{dot} to the value obtained for that wheel in step a)

- Also note that we don't use the measured ω_z but rather set it to its desired value for the arc:
  – $\omega_z = 0$ for straight arcs (no yawing desired)
  – $\omega_z = x_{dot} / r$, where is the turn radius for curved arcs

- We use the measured values for the attitude and suspension rates, which assumes those vary slowly relative to the controller frequency